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THE GLUEBALL AMONG THE LIGHT SCALAR MESONS

Wolfgang Ochs

Max-Planck-Institut für Physik, Föhringer Ring 6, D-80805 München, Germany

Abstract

The lightest gluonic meson is expected with $J^{PC} = 0^{++}$, calculations in full QCD point towards a mass of around 1 GeV. The interpretation of the scalar meson spectrum is hindered as some states are rather broad. In a largely model-independent analysis of $\pi^+\pi^- \rightarrow \pi^+\pi^-$, $\pi^0\pi^0$ scattering in the region 600-1800 MeV a unique solution for the isoscalar S-wave is obtained. The resonances $f_0(980)$, $f_0(1500)$ and the broad $f_0(600)$ or “ σ ” are clearly identified whereas $f_0(1370)$ is not seen at the level $B(f_0(1370) \rightarrow \pi\pi) \gtrsim 10\%$. Arguments for the broad state to be a glueball are recalled. We see no contradiction with the reported large $B(\sigma \rightarrow \gamma\gamma)$ and propose some further experimental tests.

1 QCD predictions for the lightest glueball

The existence of gluonic mesons belongs to the early predictions of QCD and first scenarios have been developed back in 1975¹⁾. Today, quantitative results

are available from

1. Lattice QCD: In full QCD both glue and $q\bar{q}$ states couple to the flavour singlet 0^{++} states and first “unquenched” results for the lightest gluonic state point towards a mass of around 1 GeV ²⁾. This is a considerably lower mass value than what is obtained in the pure Yang Mills theory for gluons (quenched approximation) where the lightest glueball is found at masses around 1700 MeV (recent review ³⁾). Further studies concerning the dependence on lattice spacing and the quark mass appear important.
2. QCD sum rules: Results on the scalar glueball and various decays are obtained in ⁴⁾. The lightest gluonic state is found in the mass range (750-1000) MeV with a decay width of (300-1000) MeV into $\pi\pi$ and the width into $\gamma\gamma$ of (0.2-0.3) keV. Other analyses find similar or slightly higher masses (1250 ± 200) MeV for the lightest glueball ⁵⁾.

2 The scalar meson spectrum and its interpretation

In the search for glueballs one attempts to group the scalar mesons into flavour multiplets (either $q\bar{q}$ or tetraquarks) and to identify supernumerous states. The existence of such states could be a hint for glueballs either pure or mixed with $q\bar{q}$ isoscalars. In other experimental activities one looks for states which are enhanced in “gluon rich” processes and are suppressed in $\gamma\gamma$ processes.

The lightest isoscalar states listed in the particle data group ⁶⁾ are

$$f_0(600)(\text{or } \sigma), f_0(980), f_0(1370)(?), f_0(1500), f_0(1710), f_0(2080), \quad (1)$$

where the question mark behind $f_0(1370)$ will be explained below. There are different routes to group these states into multiplets together with a_0 and K_0^* states.

In a popular approach the two lightest isoscalars in (1) are combined with $\kappa(800)$ and $a_0(980)$ to form the lightest nonet, either of $q\bar{q}$ or of $qq - \bar{q}\bar{q}$ type. Then the next higher multiplet from $q\bar{q}$ would include $a_0(1450)$, $K_0^*(1430)$; near these masses three isoscalars are found in the list (1) at 1370, 1500 and 1710 MeV and this suggests to consider these three mesons as mixtures of the two members of the $q\bar{q}$ nonet and one glueball (for an early reference, see ⁷⁾).

A potential problem in this scheme for the glueball is the very existence of $f_0(1370)$, otherwise there is no supernumerous state in this mass range. Some problems with this state will be discussed below, see also the review ⁸⁾. The

low mass multiplet depends on the existence of κ which we consider as not beyond any doubt: its observed phase motion is rather weak and it is markedly different from the one of “ σ ”, see below.

There are other approaches for the classification of the scalar mesons where $f_0(980)$ is the lightest $q\bar{q}$ scalar. In the scheme we prefer ⁹⁾ the lightest $q\bar{q}$ nonet contains $f_0(980)$, $f_0(1500)$ together with $a_0(1450)$, $K_0^*(1430)$. The supernumerous state $f_0(600)$, called previously $f_0(400 - 1200)$, corresponds to a very broad object which extends from $\pi\pi$ threshold up to about 2 GeV and is interpreted as largely gluonic. No separate $f_0(1370)$ is introduced, nor $\kappa(800)$. Our classification is consistent with various findings on production and decay processes including D, D_s, B and J/ψ decays ^{9, 10, 11)}.

Related schemes are the Bonn model ¹²⁾ with a similar mixing scheme for the isoscalars and the K-matrix model ¹³⁾ which finds a similar classification (but with $f_0(1370)$ included) and a broad glueball, centered at the higher masses around 1500 MeV.

3 Study of $\pi\pi$ scattering from 600 to 1800 MeV

3.1 Selection of the physical solution for $m_{\pi\pi} > 1000$ MeV

We are interested here in particular in the problem of $f_0(1370)$ and also in the behaviour of the broad “background” which is related to $f_0(600)$ or “ σ ”, alias $f_0(400 - 1200)$ and describe the results from an ongoing analysis (see also ¹⁴⁾).

Information on $\pi\pi$ scattering can be obtained from production experiments like $\pi p \rightarrow \pi\pi n$ by isolating the contribution of the one-pion-exchange process. In an unpolarised target experiment these amplitudes can be extracted by using dynamical assumptions, such as “spin and phase coherence”, which have been tested by experiments with polarised target. At the level of the process $\pi\pi \rightarrow \pi\pi$ in different charge states one measures the distribution in scattering angle, $z = \cos\theta^*$, or their moments $\langle Y_M^L \rangle$, in a sequence of mass intervals. The $\pi\pi$ partial wave amplitudes S, P, D, F, \dots can be obtained in each bin from the measured moments up to the overall phase and a discrete ambiguity (characterised by the “Barrelet Zeros”). The overall phase can be fixed by fitting a Breit Wigner amplitude for the leading resonances ρ , $f_2(1270)$ and $\rho_3(1690)$ to the experimental moments $\langle Y_0^2 \rangle$, $\langle Y_0^4 \rangle$ and $\langle Y_0^6 \rangle$ respectively.

Phase shift analyses of this type for $\pi^+\pi^-$ scattering have been performed

by the CERN-Munich group: an analysis guided by a global resonance fit (CM-I ¹⁵) and a fully energy-independent analysis by CM-II ¹⁷) and by Estabrooks and Martin ¹⁶); the latter two analyses found 4 different solutions above 1 GeV in mass. Up to 1400 MeV a unique solution has been found ²⁰) using results from polarised target and unitarity. Two solutions remain above 1400 MeV, classified according to Barrelet zeros in ¹⁷) as $(- - -)$ and $(- + -)$, corresponding to sols. A,C in ¹⁶).

A new result has been added recently ¹⁴) by the construction of the isoscalar S wave S_0 from the $\pi^+\pi^- \rightarrow \pi^0\pi^0$ data (GAMS collaboration ¹⁹) and the $I = 2$ scattering data. This S_0 wave shows a qualitatively similar behaviour to S_0 obtained from $\pi^+\pi^- \rightarrow \pi^+\pi^-$ scattering above, namely a resonance circle in the complex plane (Argand diagram) related to $f_0(1500)$ above a slowly moving circular background amplitude. This has lead us to select the solution $(- + -)$ as unique solution. We relate the differences in the two results to systematic errors introduced through the overall phase and the S_2 wave, but these are only slowly varying effects as function of mass.

3.2 Resonance fit to the isoscalar S wave

The resulting amplitude $S_0(- + -) = (\eta_0^0 \exp(2i\delta_0^0) - 1)/2i$ is shown in Fig. 1 using the CM-II data after correction for the more recent $I = 2$ amplitudes. The curves refer to a fit of the data (CM-II for $M_{\pi\pi} > 1$ GeV, CM-I for $M_{\pi\pi} < 1$ GeV) to an S-matrix in the space of 3 reaction channels ($\pi\pi, K\bar{K}, 4\pi$) as product of individual S-matrices for resonances $S_R = 1 + 2iT_R$

$$S = S_{f_0(980)} S_{f_0(1500)} S_{\text{broad}} \quad (2)$$

$$T_R = [M_0^2 - M_{\pi\pi}^2 - i(\rho_1 g_1^2 + \rho_2 g_2^2 + \rho_3 g_3^2)]^{-1} \times \rho^{\frac{1}{2}T} (g_i g_j) \rho^{\frac{1}{2}} \quad (3)$$

where $\rho_i = 2k_i/\sqrt{s}$. As can be seen in Fig. 1 the fit including 3 resonances gives a reasonable description of the data. For $f_0(1500)$ the fit parameters $M_0 = 1510$ MeV, $\Gamma_{tot} = 88$ MeV, $B(f_0 \rightarrow \pi\pi) = 38\%$ are obtained in remarkable agreement to the PDG numbers, despite the different approaches involved.

3.3 Note on $f_0(600)$, $\kappa(800)$ and $f_0(1370)$

The broad object is also described by a resonance form with mass parameter $M_0 \sim 1100$ MeV and width $\Gamma \sim 1450$ MeV. The elastic width is about 85%

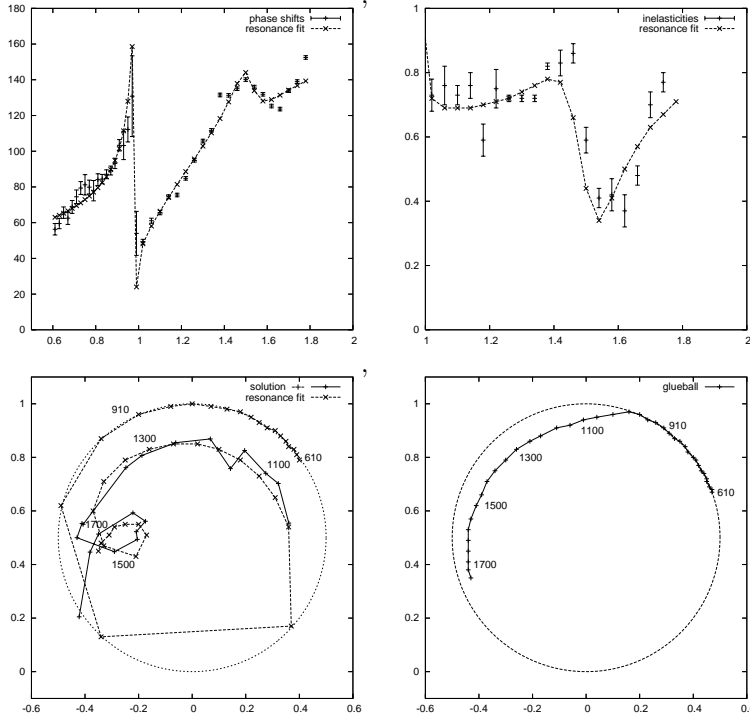


Figure 1: Resonance fit Eq. (2) in comparison with data on the corrected S_0 wave (CM-I/II): phase shifts δ_0^0 and inelasticity η_0^0 ; Argand diagram ($\text{Im } S_0$ vs. $\text{Re } S_0$); on rhs: broad component $f_0(600)/\sigma$ from the fit.

whereas the GAMS data suggest rather a smaller value around 70%. More details will be given elsewhere. This parametrisation is also shown at the lower rhs of Fig. 1. It describes about 3/4 of the full resonance circle. The Breit Wigner mass parameter M_0 denotes the mass where the amplitude is purely imaginary. It is different from the pole mass which is referred to as resonance mass. This mass value appears to be considerably lower and requires a more careful study of the line shape in the denominator of (3).

In any case, the data in Fig. 1 suggest there is evidence for a broad state in $\pi\pi$, centered around 1000 MeV along the physical region and what is called $f_0(600)$ or σ refers to the same state, there cannot be two states.

We also note here that the $\pi\pi$ scattering looks considerably different from elastic $K\pi$ scattering in that the phase of the “background” found in the analysis of the LASS data ²¹⁾ moves more slowly staying below 90° always. The existence of κ would become evident if the phase passed through 90° in forming a circle as in case of σ .

We note that the data presented in Fig. 1 do not give any indication of the existence of $f_0(1370)$ which would show up as a second circle in the Argand diagram with respective signals in η_0^0 and δ_0^0 . In fact, none of the energy-independent bin by bin analyses of the CM or CKM data ^{15, 16, 17, 18)} nor of the GAMS data ^{19, 14)} gave such an indication. From our analysis we exclude an additional state with branching ratio $B(f_0(1370) \rightarrow \pi\pi) \gtrsim 0.1$ near 1370 MeV (this would correspond to a circle of diameter 0.1).

These results from the bin-by-bin analysis are in apparent conflict with two other analyses presented at this conference ^{22, 23)}. In both studies CM-I moments as well as various other data sets from 3 body final states, have been fitted by model amplitudes with resonances in all relevant partial waves. The amplitude S_0 by Bugg ²²⁾ shows $f_0(1370)$ as an extra circle of diameter 0.25 whereas Sarantsev’s Argand diagram ²³⁾ shows no extra circle but an effect in the phase movement. Obviously, these discrepancies need to be understood.

4 Glueball interpretation of the broad object $f_0(600)$

The following arguments are in favour of this state to be a glueball ^{9, 10, 11)}.

1. This state is produced in almost all “gluon rich” processes, including central production $pp \rightarrow p(\pi\pi)p$, $p\bar{p} \rightarrow 3\pi$, $J/\psi \rightarrow \gamma\pi\pi(?)$, $\gamma K\bar{K}$, $\gamma 4\pi$, $\psi' \rightarrow \psi\pi\pi$, $\Upsilon'', \Upsilon' \rightarrow \Upsilon\pi\pi$ and finally $B \rightarrow K\pi\pi$, $B \rightarrow K\bar{K}K$ related to $b \rightarrow sg$. The high mass tail above 1 GeV is seen as “background” in $J/\psi \rightarrow \gamma K\bar{K}$ and in B decay channels where it leads to striking interference phenomena with $f_0(1500)$ ¹¹⁾.
2. Within our classification scheme ⁹⁾ without κ and $f_0(1370)$ the state $f_0(600)$ is supernumerous.
3. The mass and large width is in agreement with the QCD sum rule results and also with the first results from unquenched lattice QCD.
4. Suppression in $\gamma\gamma$ production.

Recently, the radiative width $\Gamma(f_0(600) \rightarrow \gamma\gamma) = (4.1 \pm 0.3) \text{ keV}$ has been determined by Pennington ²⁴⁾ from the process $\gamma\gamma \rightarrow \pi\pi$. As this number is larger than expected for glueballs (see Sect.1), he concluded this state “unlikely

to be gluonic". Similar results on this width are obtained by ^{25, 26)}. A resolution of this conflict has been suggested in a recent paper ²⁵⁾.

It is argued that the phenomenology of $\gamma\gamma \rightarrow \pi\pi$ at low energies is different from the one at high energies. At low energies, few 100 MeV above threshold, the photons couple to the charged pions and the Born term with one pion exchange dominates in $\gamma\gamma \rightarrow \pi^+\pi^-$, in addition there is a contribution from $\pi^+\pi^-$ rescattering. Explicit models with $\pi\pi$ scattering as input and with $f_0(600)$ pole, can explain the low energy processes ^{27, 28)}, also calculations in χPT with non-resonant $\pi\pi$ scattering at low energies ²⁹⁾. In this case of the rescattering contribution, a resonance decaying into $\pi\pi$ would also decay into $\gamma\gamma$ irrespective of the constituent nature of the state.

At high energies, the photons do resolve the constituents of the produced resonances: for example, the radiative widths of tensor mesons f_2, f'_2, a_2 in the region 1200-1500 MeV follow the expectations from a $q\bar{q}$ state.

In the model by Mennessier ²⁷⁾ the low energy rescattering and the high energy "direct" component relating to the constituents are added; the unitarization keeps the validity of Watson's theorem. A fit of the data at the lower energies $M_{\pi\pi} < 550$ MeV provides an estimate of the direct contribution from its deviation from the rescattering term. This yields $\Gamma(f_0(600) \rightarrow \gamma\gamma)|_{direct} \approx 0.3$ keV ($\pm 50\%$), alternatively, one can express this result as upper limit $\Gamma(f_0(600) \rightarrow \gamma\gamma)|_{direct} < 0.5$ keV (90%CL). This result implies that there is no contradiction with a gluonic interpretation of $f_0(600)$.

Finally, we express some expectations for experiment which follow from this interpretation.

1. Because of its large width the state $f_0(600)$ overlaps with both physical regions. Whereas the low energy region is governed by hadronic rescattering there is the transition to high energies with a resolution of the constituents. Therefore we expect that for increasing mass $M_{\pi\pi} \gtrsim 1$ GeV the decay fraction $f_0(600) \rightarrow \gamma\gamma$ decreases strongly relative to $f_0(600) \rightarrow \pi\pi$ in consequence of the weak intrinsic coupling of the glueball to $\gamma\gamma$ by an order of magnitude.
2. In processes with virtual photons the $\pi\pi$ rescattering contribution should be suppressed with respect to the direct $q\bar{q}$ coupling contribution because of the pion formfactor. This could result in a relative suppression of $f_0(600)$ production at low $\pi\pi$ mass with respect to $f_0(980)$ if the latter state is dominantly $q\bar{q}$; this should hold for both space like ($\gamma_V\gamma \rightarrow \pi\pi$) and time like photons

$(\gamma_V \rightarrow \pi\pi\gamma)$.

In this way the study of the $\pi\pi$ S wave cross section in two-photon processes (or its upper limit obtained using the positivity of the density matrix³⁰⁾) could provide new clues on the interpretation of the broad state $f_0(600)$.

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